REPORT No. 558

TURBULENCE FACTORS OF N. A. C. A. WIND TUNNELS AS DETERMINED BY SPHERE TESTS

By Robert C. Platt

SUMMARY

Results of drag and pressure tests of spheres having diameters of 2, 4, 6, 8, 10, and 12 inches in eight N. A. C. A. wind tunnels, in the air ahead of the carriage in the N. A. C. A. tank, and beneath an autogiro in flight are presented in this report. Two methods of testing were employed, one involving measurements of sphere drag and the other measurements of the pressure difference between the front stagnation point and the rear portion of the sphere. Satisfactory correlation between the two methods was obtained experimentally, as set forth in an appendix to the report.

The following table indicates the relative status of the wind tunnels tested as regards the amount of turbulence normally encountered in their air streams, the least-turbulent being listed first:

Full-scale tunnel.
24-inch high-speed tunnel.
20-foot tunnel.
Model of the full-scale tunnel.
7- by 10-foot tunnel.
5-foot vertical tunnel.
Free-spinning tunnel.
Variable-density tunnel.

A "turbulence factor" for each wind tunnel, defined as the ratio of the critical Reynolds Number of a sphere in a nonturbulent air stream to the critical Reynolds Number in the tunnel, was obtained from sphere-test results. When the Reynolds Number of a model tested in a wind tunnel is multiplied by the turbulence factor for that tunnel, the resulting value is an "effective" Reynolds Number; that is, the Reynolds Number at which certain critical flow conditions obtained in the actual test would be approximately reproduced in a nonturbulent stream. When this method is used to obtain the scale-effect variation of maximum lift coefficient and drag coefficient at zero lift of certain well-known airfoils, data obtained in various wind tunnels under a wide variety of turbulent conditions are brought into satisfactory agreement.

INTRODUCTION

Air-stream turbulence has long been recognized as a source of discrepancy between forces measured on a model in a wind tunnel and forces that would occur on the model in free air under otherwise comparable conditions. Although the general effects of turbulence are now fairly well known, present knowledge is insufficient to permit either an exact determination of the nature and quantity of turbulence present in an air stream or the development of satisfactory corrections for its effect. It is possible, however, to determine by any one of several experimental methods a value indicative of the relative magnitude of the turbulence present in an air stream.

The effect of wind-tunnel turbulence in general on the aerodynamic characteristics of bodies has been estimated in some specific cases by the introduction of artificial turbulence into the tunnel air stream. In such cases an approximate determination of the amount of turbulence introduced relative to the initial turbulence has been of considerable assistance in extrapolating to the condition of zero turbulence. It is thus apparent that approximate measurements of air-stream turbulence, even though they fail to give completely satisfactory corrections, are of definite significance in wind-tunnel research.

A method commonly used to determine the turbulence of a wind tunnel involves measurement of the change in the drag coefficient of a sphere as the Reynolds Number of the sphere is varied. This method depends on a change in the nature of the flow about a sphere with changing Reynolds Number. At a low value of the Reynolds Number the flow separates approximately at the equator of the sphere and a large eddying wake with low pressure on the downstream side of the sphere results. In this condition the boundary layer of the sphere ahead of the point of separation is laminar. As the Reynolds Number is increased, transition from laminar to turbulent flow moves ahead of the point of separation with a resulting backward, or downstream, movement of the point of separation and a consequent reduced wake area and drag. The Reynolds Number at which this sudden change of flow takes place has been called the "critical Reynolds Number." The change from laminar to turbulent flow in the boundary layer depends on the Reynolds Number and the initial turbulence of the air stream in such a way that the initial turbulence decreases the value of the Reynolds Number at which transition from laminar to turbulent flow in a boundary layer takes place. Thus the value of the critical Reynolds Number serves to indicate the amount of turbulence present in the air stream. In an extensive investigation by Dryden and Kuethe (reference 1) a relation was established between the critical Reynolds Number of a sphere in an air stream and the percentage turbulence of the air stream. The paper gives a clear account of the basic theory and proposes a quantitative method of determining the initial turbulence of an air stream from drag tests of spheres.

Sphere tests have come to be regarded as essential to the calibration of a wind tunnel, and some data of this nature have already been obtained in most of the existing wind tunnels. References 2 and 3 present the results of previous N. A. C. A. sphere tests in free air, in the old atmospheric wind tunnel, and in an early modification of the variable-density tunnel. The data obtained in the present investigation, however, are the first published material applicable to the various N. A. C. A. wind tunnels in their present forms.

The investigation was undertaken with the intention of determining the comparative turbulence of the present N. A. C. A. wind tunnels in such a way as to obtain an estimate of the effect of turbulence on test results. It was considered desirable to determine, if possible, the changes in aerodynamic characteristics resulting from the different turbulent conditions existing in free air and in wind tunnels. The determination of the comparative turbulence of free air was therefore considered an additional object of the investigation. The investigation was conducted during 1933–35 at such times as each of the eight tunnels at present in use became available.

APPARATUS AND METHODS

Wind tunnels.—The eight wind tunnels investigated, with references to descriptive material, are listed in the following table:

The 7- by 10-foot tunnel, reference 4.
The model of the full-scale tunnel, reference 5.
The full-scale tunnel, reference 6.
The 20-foot wind tunnel, reference 7.
The 5-foot vertical tunnel, reference 8.
The 24-inch high-speed tunnel, reference 9. (Reference 10 gives a description of a similar high-speed tunnel of smaller size.)
The variable-density tunnel, reference 11.
The free-spinning tunnel, reference 12.

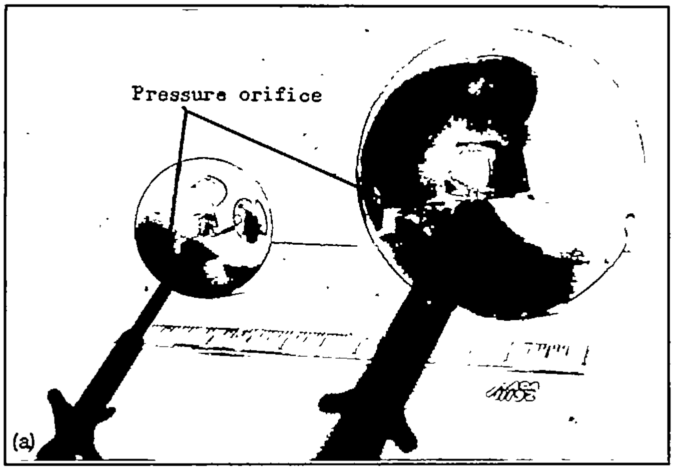
Data for free air were obtained by towing spheres beneath an autogiro in flight and ahead of the carriage in the canopy of the N. A. C. A. tank (reference 13).

Spheres.—Tests were made of five mahogany spheres (fig. 1(b)) having diameters of 4, 6, 8, 10, and 12 inches; the spheres were finished with lacquer and polished smooth. They were mounted on stings which could be attached to a balance for drag tests and which, in normal test position, extended directly downstream from the center of the sphere. Two holes, one at the front stagnation point and one 22° from the downstream axis of the sphere, were equipped with pressure leads to permit measurement of the front and rear pressures on each sphere. In addition to the wooden spheres, an 8-inch hard rubber bowling ball, a 2-inch steel ball bearing, and a 4-inch brass ball were used in some of the tests. The rubber sphere, which had a smooth, rubbed finish and which was not equipped with pressure holes, served as a check of the surface finish of the wooden spheres, which had to be repolished several times during the course of the tests. The steel and brass spheres (fig. 1(a)), which had only rear pressure holes, were polished to a mirror finish; they, in addition to serving as checks of the surface finish of the other spheres, were used for tests in which the other spheres were unsuitable. The nose pressures for these spheres were obtained from tunnel calibration data.

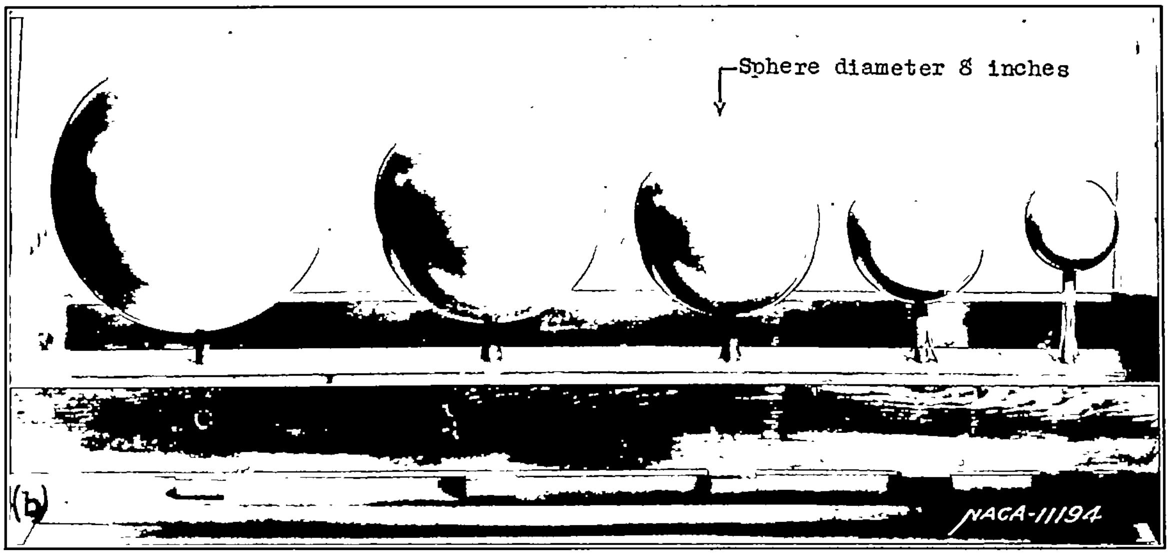
Balance and supports.—A portable drag balance (fig. 2a, b) especially designed to be easily mounted in various wind tunnels was constructed for use in this investigation. This balance consists of a round bar supported on Emery knife-edges inside a 2¼-inch tube. The bar, which has a tapped hole in the forward end to take the sphere-support sting, is restrained longitudinally by a calibrated pressure capsule and can be balanced between contact points. The pressure required to produce balance is a measure of the drag force on the sphere.

A towing support (fig. 3) for use in making pressure measurements on the spheres was also constructed. This support consists of a bar with fins at the rear and with a tapped hole in the nose to take the sphere-support sting. With the sphere in place the unit was supported at its center of gravity by a cable and hung in any desired position with respect to an airplane, to the carriage of the N. A. C. A. tank, or in the air stream of a wind tunnel.

Drag measurements.—For the drag measurements the special balance was supported rigidly in the tunnel under investigation and the drag forces on each of several spheres were measured at various air speeds. Drag measurements were made in the 7- by 10-foot tunnel, the model full-scale tunnel, and at two positions in the jet of the full-scale tunnel. In the 7- by 10-



(a) Metal spheres.



(b) Wooden spheres.

FIGURE 1.—Spheres used in the turbulence tests.

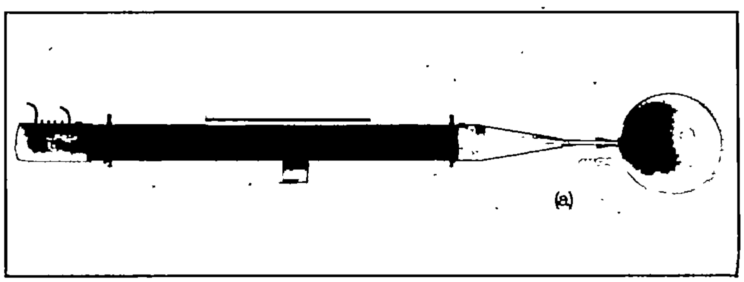


FIGURE 2a.—An 8-inch sphere mounted on the drag balance.

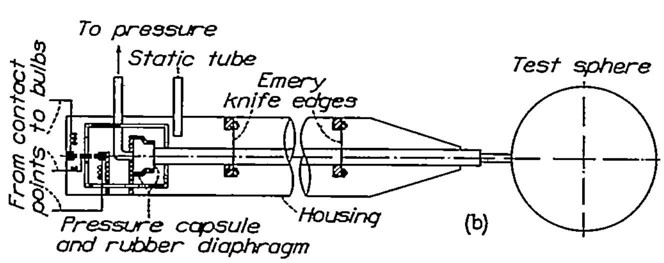


FIGURE 2b.—Sketch of the sphere drag balance.

foot-tunnel tests, two conditions of turbulence were obtained, one in the clear tunnel and one with a turbulence grid in the jet ahead of the sphere. This grid consisted of ¼-inch square bars set edge on to the stream with their axes spaced 1½ inches. The bars extended vertically and the entire unit was located 35 inches ahead of the center of the sphere.

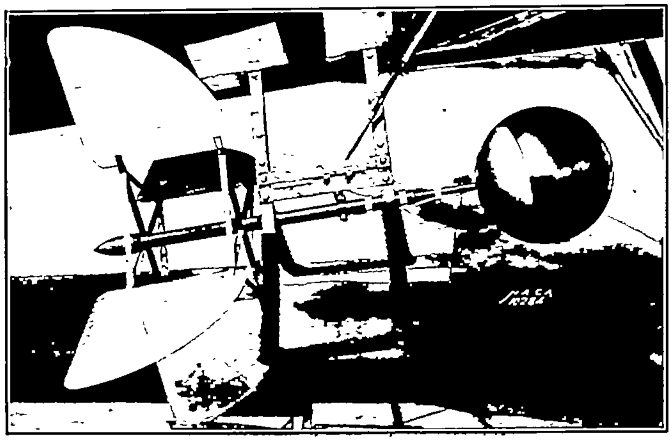


FIGURE 3.—Sphere towing unit with 10-inch sphere mounted on an autogiro.

Pressure measurements.—An alternative method of obtaining the critical Reynolds Number of a sphere was suggested for use in this investigation by Dr. H. L. Dryden, of the National Bureau of Standards. This method consists of measuring the difference of pressure Δp between the front and rear portions of the sphere. If a pressure coefficient $\Delta p/q$ is plotted against appropriate values of Reynolds Number, a variation similar to the variation of the drag coefficient with Reynolds Number is found, thus permitting an approximate determination of the critical Reynolds Number. The method was independently developed by the D. V. L. in Germany; a complete description of the theory underlying it and the results of tests in which it is used have been published in reference 14. A résumé of the theory and a description of the tests correlating drag and pressure measurements are given in an appendix to the present report. The pressure method offers considerable advantage as compared with drag tests on account of the greater ease and rapidity with which results can be obtained both in flight and in wind tunnels. In addition, greater accuracy should result from the simplification of the technique of testing and the elimination of the need for damping the balance vibration.

Pressure tests were made at model location in the 7- by 10-foot tunnel with two conditions of turbulence and with normal turbulence in all of the other tunnels previously listed with the exception of the model of the full-scale tunnel, in which no pressure tests were made. In flight and in the tank, data were obtained solely by the pressure method.

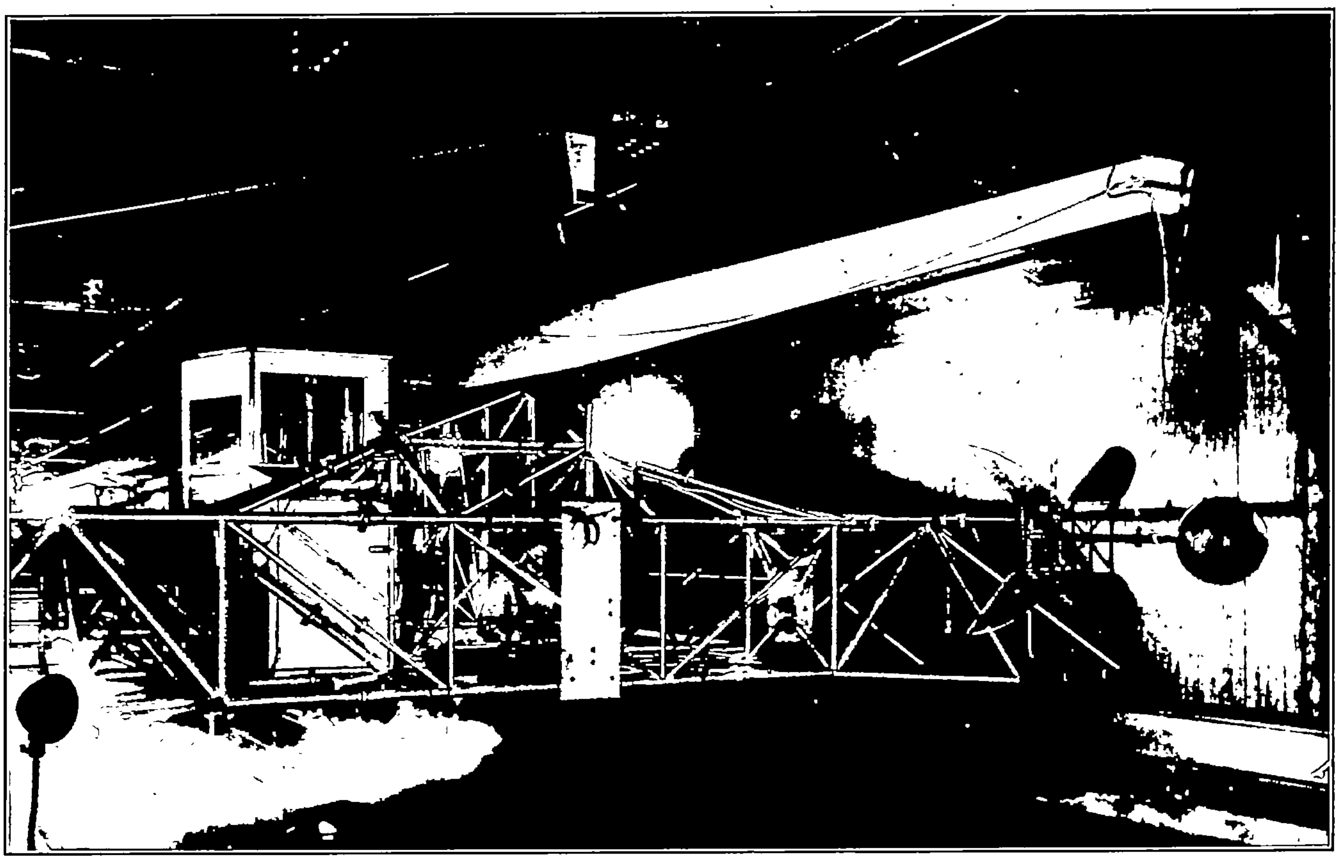


FIGURE 4.—Sphere towing unit in the N. A. C. A. tank.

Mounting of spheres.—Several methods of mounting the spheres in the wind tunnels were employed. For the drag tests the drag balance was rigidly supported either by wires or by a clamp on a streamline tube braced with wires. In each case the center line of the sphere, sting, and balance unit was accurately alined with the air stream. For some of the pressure tests the sphere was supported rigidly in the tunnel by wires attached to its sting. For the other pressure tests the towing support was hung by a V of wires permitting it to swing fore and aft but restraining the lateral motions. The fins in each case caused the sphere to maintain proper alinement in the air stream. In flight the sphere-towing support (fig. 3) was hung 70 feet below an autogiro by a cable. For the tests in the N. A. C. A. tank the towing support was hung on a special suspension of low frequency to reduce vibration of the sphere and was supported 15 feet ahead of the towing carriage near the center of the cross section of the tank canopy (fig. 4).

PRECISION

In general, errors in the sphere tests may be ascribed to faulty determination of the support interference and tare forces, to surface roughness, and to vibration of the sphere and the support. Support interference may be divided into two types: First, that resulting from a change in air flow caused by the junction of the support and sphere; and second, that resulting from a change in the air flow induced by the presence of bodies, such as the drag balance, behind the sphere.

The first type of support interference may be reduced to a negligible amount by having the point of attachment of the sphere to its support at the most downstream point of the sphere and by keeping the size of the support relatively small as compared with the size of the sphere (references 2 and 14). Satisfactory agreement between pressure measurements of duplicate set-ups with and without the sphere-drag balance in place indicates that the second type of interference is also negligible in these tests. Attempts to measure any tare force on the drag balance were unsuccessful. Since it is reasonable to suppose that errors in tare-force determination would be approximately proportional to the magnitude of the tare force itself, it seems probable that errors resulting from this source are very small. In cases where the nature of the support permitted visible vibration of the sphere, it was found that the critical Reynolds Number was appreciably reduced and care was taken to keep vibration at a minimum during the course of the testing.

From comparison of the results of check tests, it is believed that the variation of the observed critical Reynolds Number caused by accidental errors lies within the following limits:

Drag tests in wind tunnels	±5,000
Pressure tests in wind tunnels	±5,000
Pressure tests in flight	±8,000
Pressure tests in tank	±5,000

The tests in flight and in the tank are thought to be free from error due to vibration because of the support employed. It seems very unlikely that vibrations from the autogiro could be transmitted down the 70-foot length of flexible cable used in the flight tests. The special spring suspension used in the tank showed a strong tendency to damp vibrations. Air turbulence as indicated by the motion of titanium tetrachloride smoke is considered to have been nonexistent in the air encountered by the sphere during the test runs in the tank canopy.

RESULTS AND DISCUSSION

Presentation of results.—Test data from the drag and the pressure tests have been reduced to the following nondimensional coefficient forms:

Drag coefficient, $C_D=\frac{\text{drag force}}{qS}$

Pressure coefficient, $\frac{\Delta p}{q}$

in which $q=\frac{1}{2}\rho V^2$, dynamic pressure.

$S=\frac{\pi d^2}{4}$, cross-sectional area of sphere.

d, sphere diameter.

Δp, the pressure difference between the front and rear orifices in the sphere.

The values of the drag and the pressure coefficients are then plotted against Reynolds Number Vd/ν, in which V is the velocity of the air stream and ν is the kinematic viscosity of the air. The critical Reynolds Number R_c is chosen as that value of the Reynolds Number corresponding to a drag coefficient of 0.3 (reference 1) or to a pressure coefficient of 1.22 in accordance with the correlation of the results of the drag and pressure tests presented in the appendix.

The 7- by 10-foot wind tunnel.—Results of drag and pressure tests in the 7- by 10-foot wind tunnel are shown in figures 5 and 6. Figure 5 (a, b, c, d) shows curves of C_D and $\Delta p/q$ for spheres of different size in the clear tunnel, with normal turbulence. Figure 6 (a, b, c, d) shows curves of C_D and $\Delta p/q$ for different spheres in the tunnel with the turbulence grid in place. The discontinuity in the $\Delta p/q$ curve for the 8-inch sphere in figure 6 (c) should be noted as a phenomenon that has appeared in several other tests as well as in this one. (In such cases it has been possible to repeat these

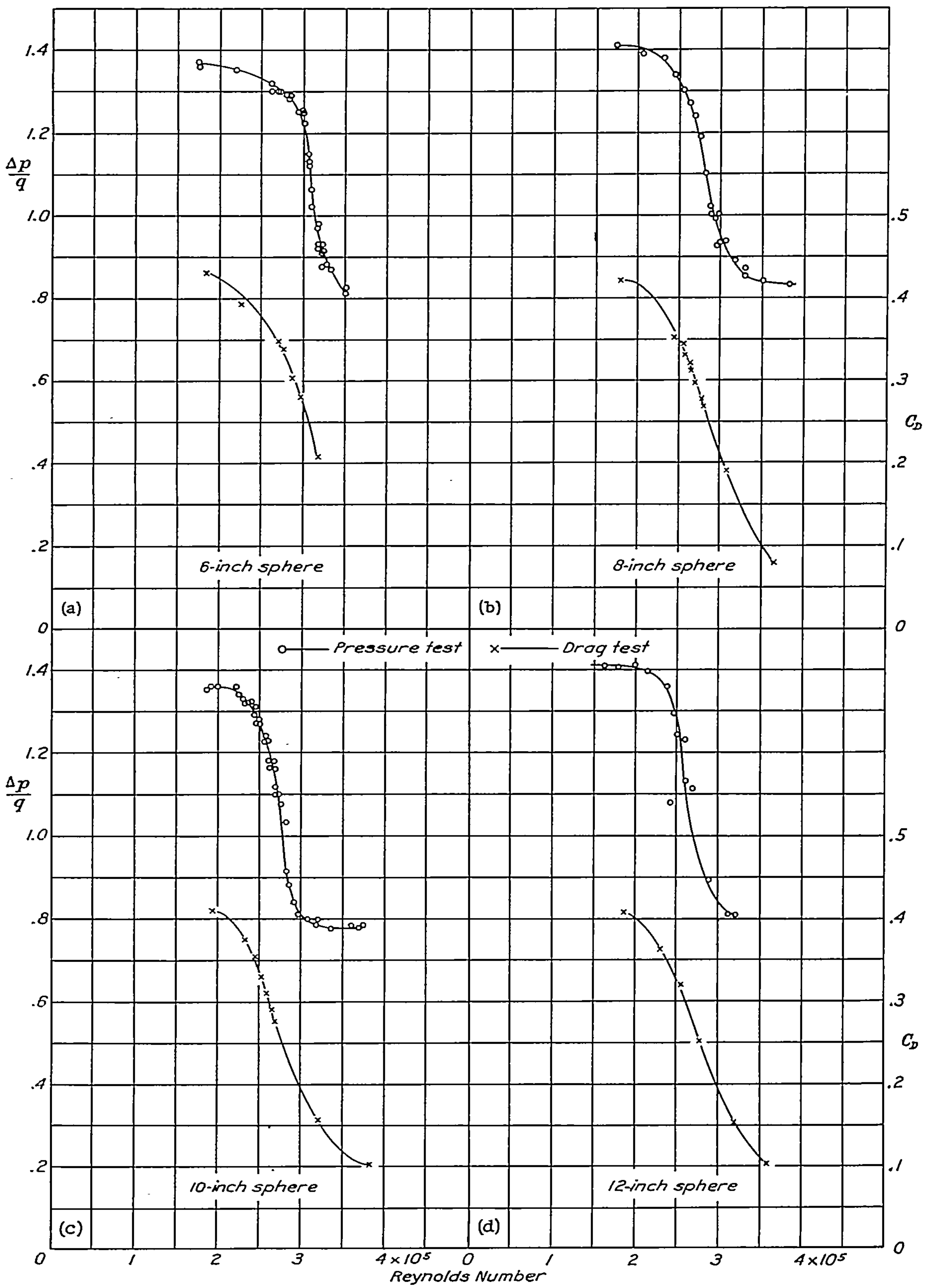


FIGURE 5 (a, b, c, d).—Pressure and drag tests of spheres of different size in the 7- by 10-foot wind tunnel with normal turbulence.

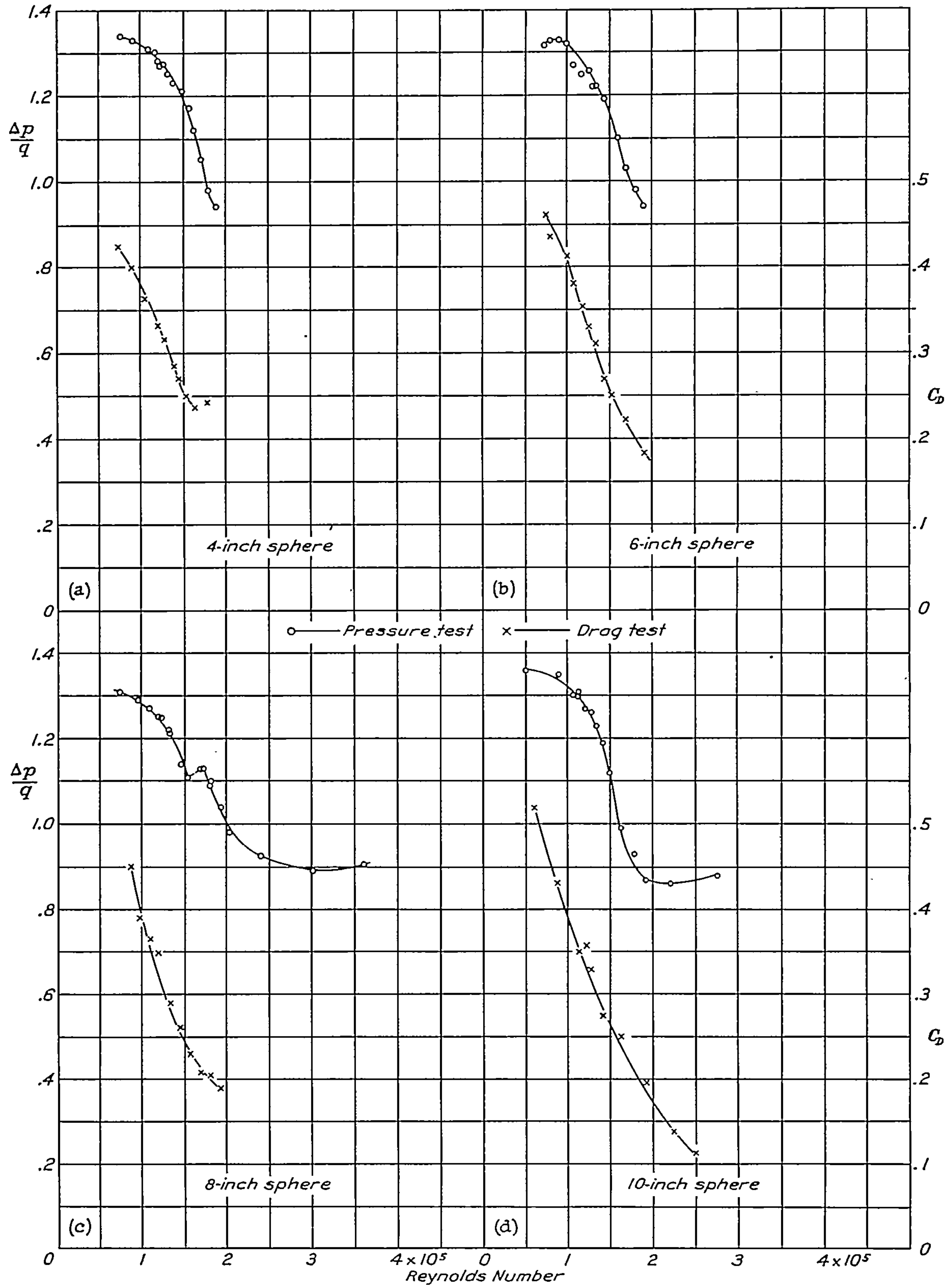


FIGURE 6 (a, b, c, d).—Pressure and drag tests of spheres of different size in the 7- by 10-foot wind tunnel with turbulence grid.

points in check tests.) Inasmuch as it does not, in general, extend to the critical value of $\Delta p/q$, no special consideration has been given to it in this investigation.

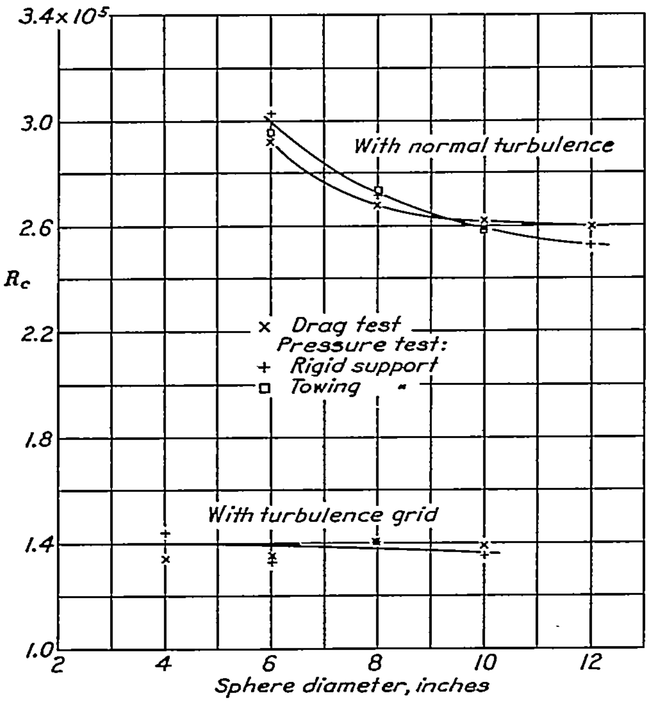


FIGURE 7.—Variation of critical Reynolds Number with sphere diameter in the 7- by 10-foot wind tunnel.

Figure 7 shows the variation of critical Reynolds Number with sphere diameter. Since the air speed at which the critical Reynolds Number on a sphere occurs varies with the size of the sphere, it is possible that the

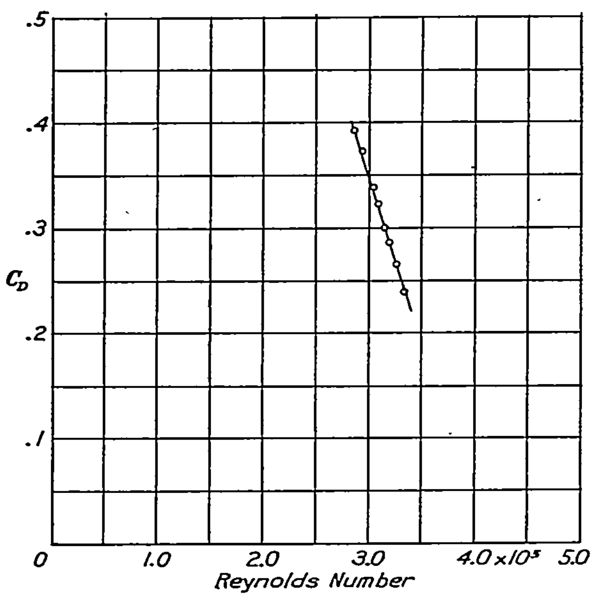


FIGURE 8.—Sphere drag test in the model full-scale wind tunnel with the 8-inch sphere.

observed variation of the critical Reynolds Number with sphere size may result from a variation in tunnel turbulence with air speed. The fact that the energy ratio of the wind tunnel changes with air speed tends to support this view, although data of references 1 and 15 indicate that the turbulence as measured by a hot-wire turbulence indicator is independent of the tunnel air speed. Although Harris and Graham (reference 16) suggest that the value of R_c varies with the ratio of sphere to tunnel diameter, subsequent data (discussed in Summary of Test Results) in the present report tend to invalidate this explanation of the observed effect. Figure 7 also shows the agreement of the pressure tests with the sphere supported on the drag balance and mounted at the same position in the air stream on the towing support. As stated previously, the agreement

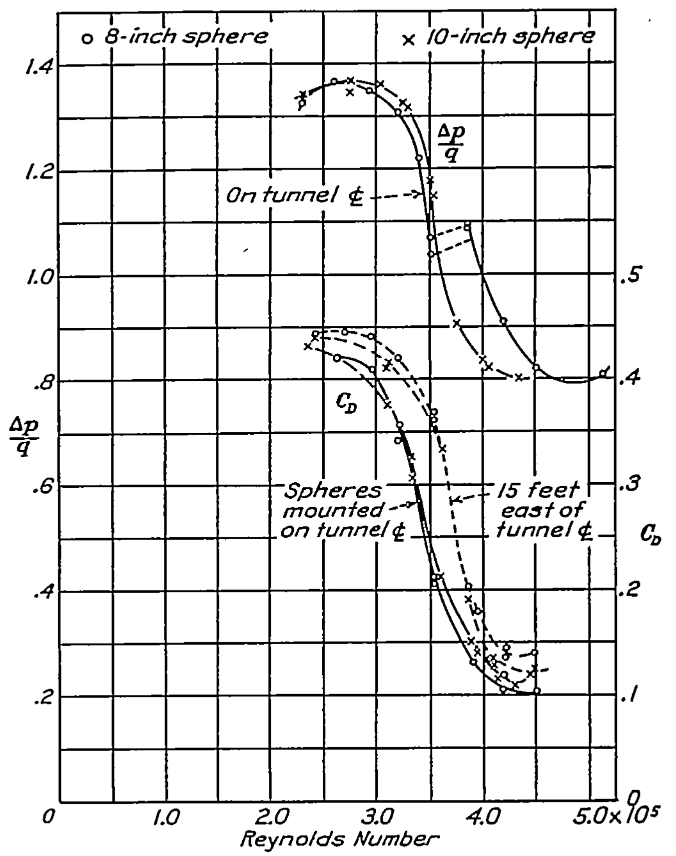
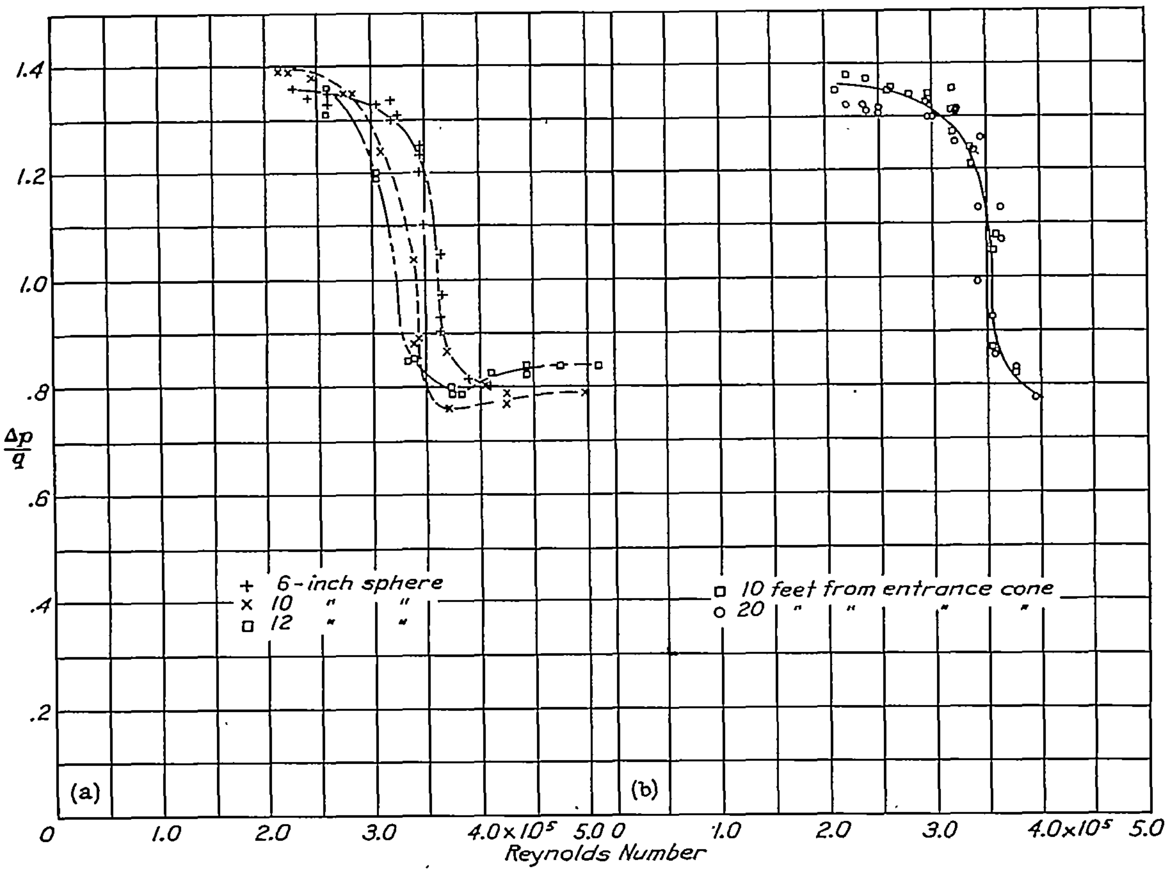


FIGURE 9.—Pressure and drag tests of spheres of different size in the full-scale wind tunnel with normal turbulence.

between the tests indicates that the presence of the drag balance behind the sphere does not exert an appreciable effect on the air flow in the tunnel.

Model of the full-scale tunnel.—Results of drag tests on an 8-inch rubber sphere, the one test made in the 1/15-scale model of the full-scale tunnel, are shown in figure 8.

Full-scale tunnel.—Results of drag tests on two wooden spheres, each mounted 15 feet east of the vertical center line of the full-scale tunnel and on its horizontal center, and results of both drag and pressure tests with the spheres mounted at the intersection of the tunnel center lines are shown in figure 9. It is note-



(a) Three spheres mounted on tunnel center line. (b) The 6-inch sphere mounted 2½ feet east of tunnel center line.

FIGURE 10.—Pressure tests of spheres of different size in the 20-foot wind tunnel with normal turbulence.

worthy that the turbulence appears to be definitely less 15 feet away from the center of the tunnel than on its vertical center line. A possible cause of the increased turbulence at the center may be the junction of the turbulent boundary layers from the outer walls of the return passages into a single disturbed region along the center of the jet.

Twenty-foot wind tunnel.—Results of pressure tests with three wooden spheres each mounted at various positions in the jet of the 20-foot wind tunnel are shown in figure 10 (a, b). As the full-scale and 20-foot tunnels have similar types of double return passage, it was intended to make tests at a position 5 feet off center, corresponding to the off-center position in the full-scale tunnel, but in this position it was found that an unsteadiness of flow in the jet caused the towing support to move unsteadily in the air stream, preventing satisfactory observation of the pressure differences. Tests were made 2½ feet off center where no unsteadiness was observed. No apparent difference was found in the amount of turbulence 10 feet and 20 feet from the entrance cone of this tunnel, which is in disagreement with the general belief that turbulence tends to be damped in an air stream. It is possible, however, that the turbulence had been so completely damped when the air reached the 10-foot station that there was very little further damping as it passed downstream.

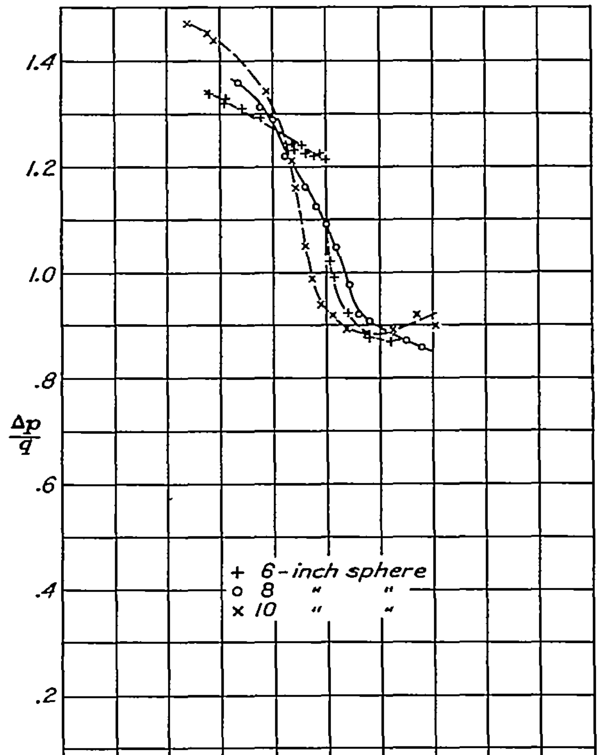
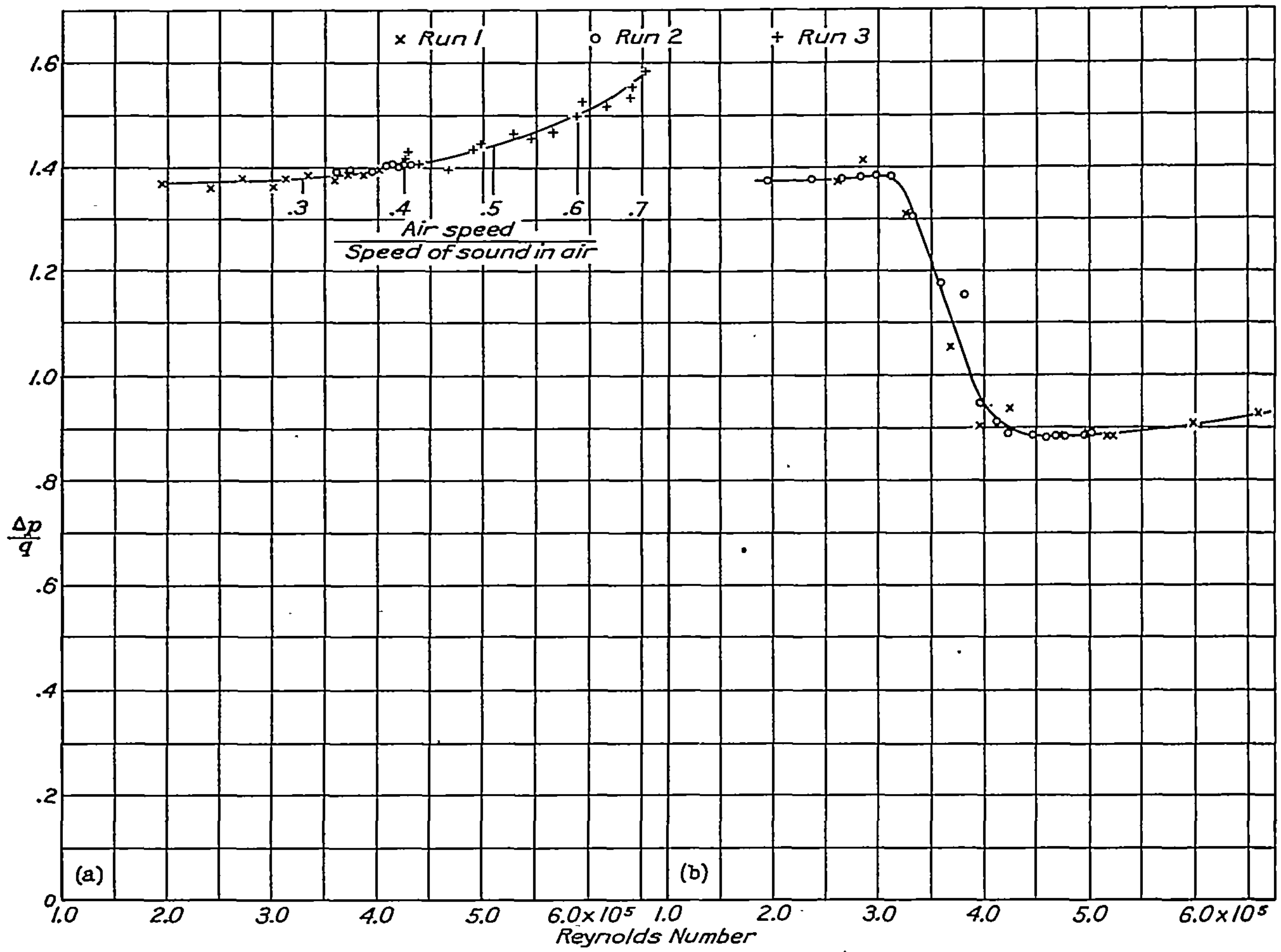


FIGURE 11.—Pressure tests of spheres of different size in the 5-foot vertical wind tunnel with normal turbulence. Spheres mounted on tunnel center line.

Five-foot vertical tunnel.—Results of pressure tests of three wooden spheres each located on the center line of the 5-foot vertical tunnel at the normal test position are shown in figure 11.

The 24-inch high-speed tunnel.—Results of pressure tests of the 2-inch steel and the 4-inch brass spheres in the 24-inch high-speed tunnel appear in figure 12 (a, b). Some tests of wooden spheres conducted before the final modifications and calibration of the tunnel indicated the 4½-inch off-center station to be representative of the average conditions across the jet at test level, and this position was accordingly chosen for the final tests.



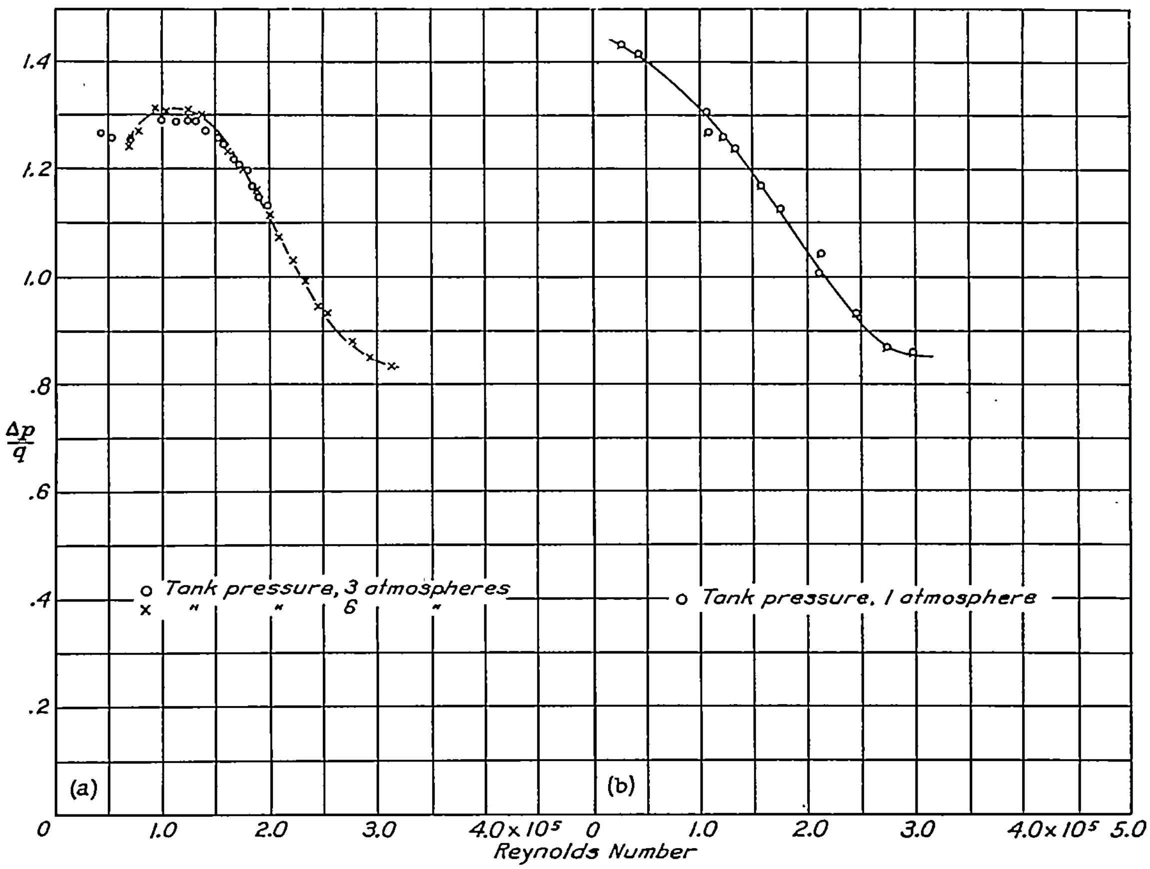
(a) The 2-inch sphere mounted 4½ inches south of the tunnel center line. (b) The 4-inch sphere mounted 4½ inches south of the tunnel center line.

FIGURE 12.—Pressure tests of two spheres in the 24-inch high-speed wind tunnel with normal turbulence.

The failure of the 2-inch sphere to reach a critical Reynolds Number is an interesting and apparently hitherto unobserved phenomenon. At a Reynolds Number of slightly over 300,000 where the pressure coefficient should begin to drop sharply, it begins to rise at a steadily increasing rate, giving a shape of curve suggestive of the variation of drag of an airfoil with air speed in the region in which compressibility begins to show an effect (references 9 and 10). It seems reasonable to conclude that the failure to obtain a critical Reynolds Number may be ascribed to an effect of compressibility in delaying the onset of boundary-layer turbulence, possibly through changing the pressure gradients on which compressibility is known to exert a powerful effect. It has been suggested that such an action might have occurred on the 4-inch sphere as well, resulting in a fictitious value of the critical Reynolds Number. The effect might be suggested as an explanation of the variation of the critical Reynolds Number with sphere diameter, although such an explanation seems very unlikely in the case of the observed variation in low-speed wind tunnels.

It is clear that at speeds greater than 0.4 the velocity of sound the effects of turbulence are seriously altered by compressibility, and full account of this effect must be taken before the significance of sphere tests in this range of speeds can be understood.

Variable-density tunnel.—Results of pressure tests of the 2-inch steel sphere and the 8-inch mahogany sphere in the variable-density tunnel are shown in figure 13 (a, b). The results of tests at two different tank pressures, 3 and 6 atmospheres, indicate that variation of tank pressure does not exert an appreciable effect on the results of the sphere tests (see also reference 3); that is, variation of the pressure coefficient with Reynolds Number is the same regardless of the combination of speed and pressure used to produce a given Reynolds Number. Some tests at different positions indicate the variation of turbulence across the jet of the variable-density tunnel to be small. A comparison of the results for the 8-inch sphere with those for the 2-inch sphere indicate approximately the same variation of the critical Reynolds Number with the sphere size as has been found in the tests in other tunnels.

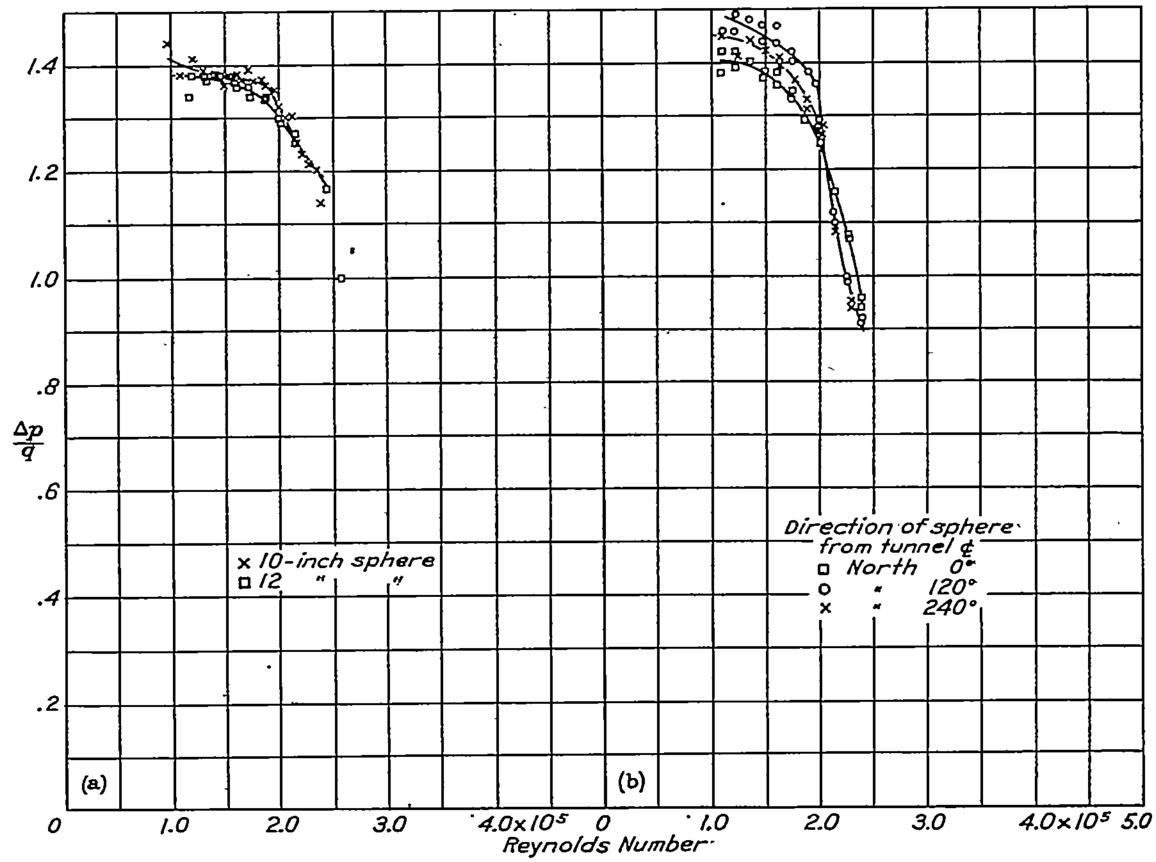


(a) The 2-inch sphere mounted on the tunnel center line. (b) The 8-inch sphere mounted on the tunnel center line.

FIGURE 13.—Pressure tests of two spheres in the variable-density wind tunnel with normal turbulence.

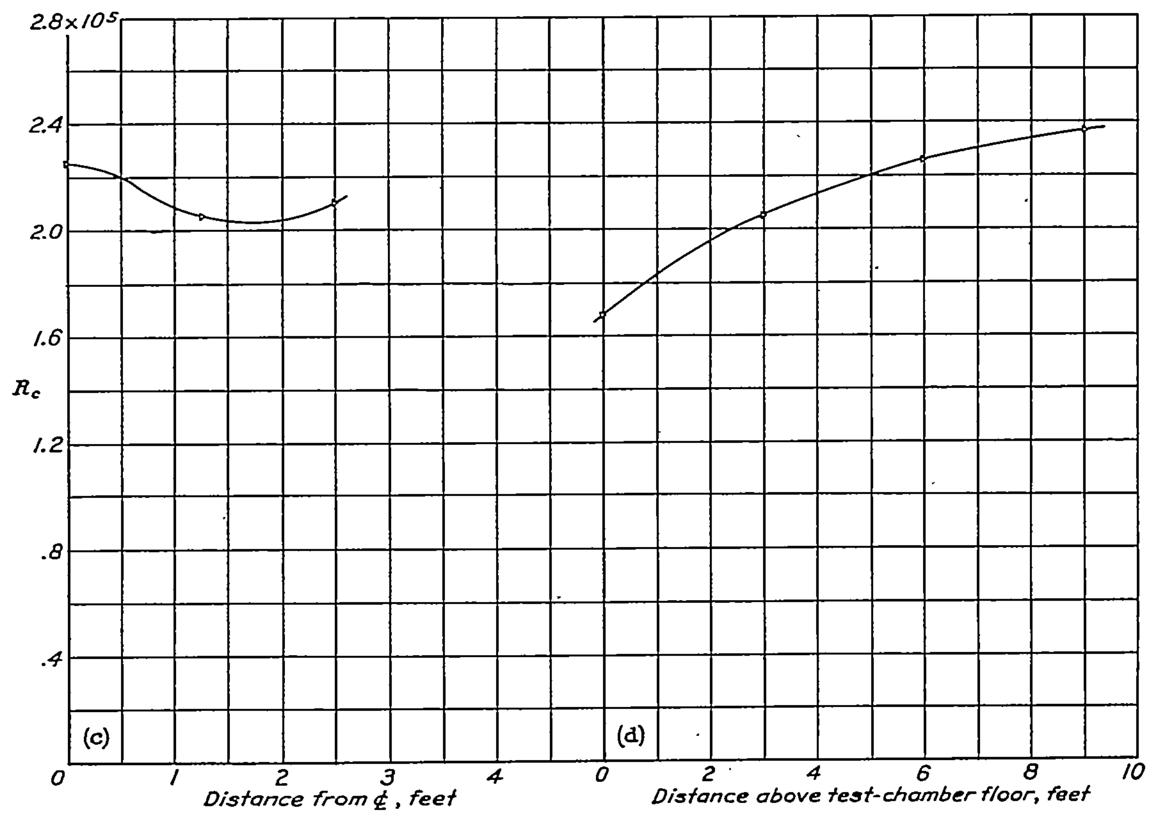
Free-spinning tunnel.—Some results of tests of the 10-inch and 12-inch spheres and the variation of critical Reynolds Number with position in the jet of the free-spinning tunnel are shown in figure 14 (a, b, c, d). The low maximum speed available in the tunnel (50 feet per second) permitted testing only the large spheres; consequently only a small range of Reynolds Numbers was covered. In this tunnel the turbulence appears to be damped as the air passes downstream. Although this variation is apparently in disagreement with that found in the 20-foot tunnel, in which the turbulence was unaffected by downstream location, it is to be noted that there is definitely more turbulence in the free-spinning tunnel and that the test positions are much nearer to the source of turbulence than is the case in the 20-foot tunnel. The curve in figure 14 (d) appears to tend toward an asymptote and it might reasonably be supposed to check the indications of the 20-foot tunnel results satisfactorily if it were extended sufficiently far along the stream.

N. A. C. A. tank.—Pressure tests of two spheres each hung in the air 15 feet ahead of the towing carriage in the N. A. C. A. tank are shown in figure 15. Values of the pressure coefficient were obtained with the 10-inch sphere up to Reynolds Numbers of 350,000, the highest value obtainable with this sphere at the maximum speed of the carriage (approximately 80 feet per second). Corresponding pressure coefficients for the 12-inch sphere were obtained up to a Reynolds Number of 475,000. The curve for the 10-inch sphere appears to extrapolate satisfactorily through the value of the critical Reynolds Number indicated by the 12-inch sphere, that is, 385,000. Since the air is known to have been very still during the tests in which this value was obtained, it is considered representative of nonturbulent air. This



(a) Two spheres mounted on tunnel center line 6 feet above test-chamber floor.

(b) The 12-inch sphere mounted 1¼ feet from tunnel center line and 6 feet above test-chamber floor.



(c) Variation of critical Reynolds Number across jet 6 feet above test-chamber floor. (d) Variation of critical Reynolds Number along the jet center line.

FIGURE 14. Pressure tests of two spheres in the 15-foot free-spinning wind tunnel with normal turbulence.

value agrees with the data presented in reference 14, in which the highest value of the critical Reynolds Number found with a sphere mounted above a motor car and tested in calm weather was 385,000. The value of 405,000 published in the reference resulted from the use of a slightly different value of the pressure coefficient $\Delta p/q$ as a criterion of the critical Reynolds Number.

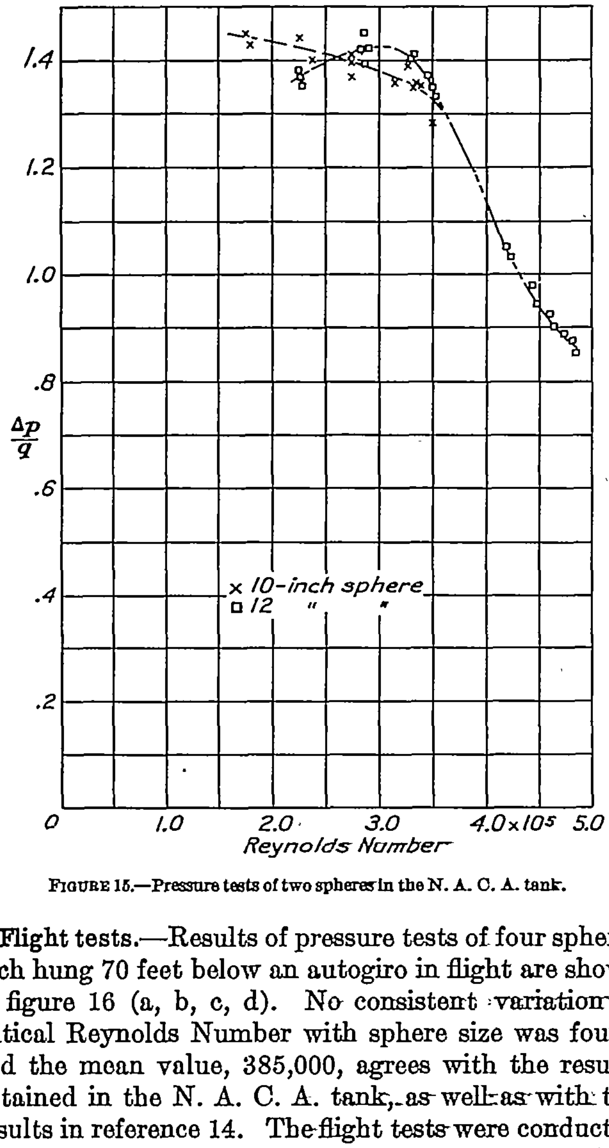


FIGURE 15.—Pressure tests of two spheres in the N. A. C. A. tank.

Flight tests.—Results of pressure tests of four spheres each hung 70 feet below an autogiro in flight are shown in figure 16 (a, b, c, d). No consistent variation of critical Reynolds Number with sphere size was found and the mean value, 385,000, agrees with the results obtained in the N. A. C. A. tank, as well as with the results in reference 14. The flight tests were conducted at altitudes of 2,000 to 5,000 feet in good weather but with varying amounts of wind. The results appear to indicate that under normal conditions the atmosphere may be regarded as nonturbulent insofar as its effect on flow about bodies having boundary layers of thickness comparable with those on the spheres used is concerned.

Summary of test results.—Average values of critical Reynolds Number for the wind tunnels investigated as well as for a number of other wind tunnels listed in references 14 and 16 appear in table I. Figure 17 shows the variation of critical Reynolds Number with sphere diameter for the cases in which these data were obtained. All these wind tunnels show a fairly consistent variation with sphere size except the full-scale tunnel, which is the least turbulent of all those investigated and which appears to give conditions more directly comparable with those found in free air.

This consistent variation in the case of tunnels like the 20-foot tunnel and the 7- by 10-foot tunnel indicates that the explanation of the effect as depending directly on ratio of sphere to tunnel diameter is erroneous. It seems very unlikely that the sizes of sphere actually used could in any case have an effect on the 20-foot-tunnel jet comparable with their effect on the 7- by 10-foot jet. The most reasonable explanations suggested up to the present have involved the idea that flow similarity for spheres of different size in the same air stream does not exist because of the different ratio between turbulence grain and sphere diameter. Evidence at present available, however, seems insufficient to justify a definite conclusion regarding this matter.

CORRECTION OF AIRFOIL TESTS

It has been proposed (reference 17) that turbulence and Reynolds Number may be regarded as variations of the same fundamental phenomenon in that aerodynamic characteristics of bodies subject to scale effect are in general also subject to an effect of turbulence. Known effects of scale and turbulence on the air flow about bodies may be divided into two general types: First, an effective increase of viscosity in the fluid due to turbulent mixing; second, the effect of turbulence on characteristics associated with transition from laminar to turbulent flow in boundary layers and its relation to flow separation. It is worthy of note, at this point, that the turbulence normally present in a wind tunnel is of small magnitude as compared with that in the turbulent boundary layer of a model and that its effect on a laminar boundary layer ahead of the point of transition to turbulent flow appears to be negligible except in reducing the stability of the laminar boundary layer against the transition. (See reference 17.) The first type of scale and turbulence effect is characterized by a slow, continuous change of coefficient with Reynolds Number apparently related to the changing ratio of boundary-layer thickness to characteristic length of the body as, for example, in the case of the drag coefficient of a streamline body. (See reference 1, et al.) The second type is characterized by a more sudden change between two states of flow, one resulting from separation of the laminar boundary layer, the other from delayed separation of the turbulent boundary layer. In this category lie the effects of scale and turbulence that are observed in sphere-drag tests and on the maximum lift of airfoils. An intermediate state of flow, in which the transition of a free, or separated, boundary layer is the important factor

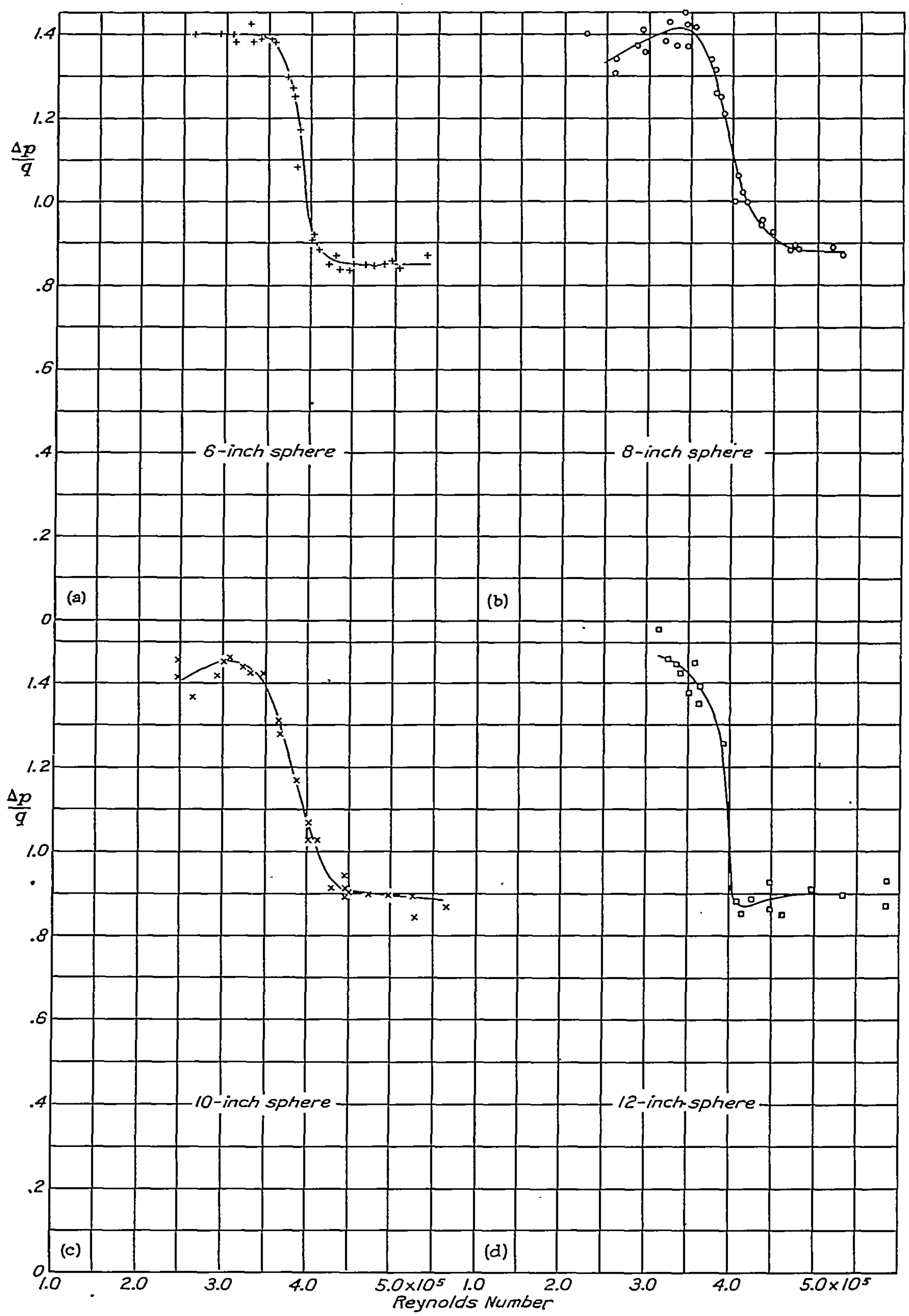


FIGURE 16 (a, b, c, d)—Pressure tests of spheres of different size towed beneath an autogiro in flight.

(reference 17), may exist and should not be excluded from considerations of the second type of scale and turbulence effect.

The variation of the maximum lift of an airfoil with Reynolds Number (see, for example, references 15 and 18) has been ascribed to the tendency of the turbulent boundary layer to delay separation of flow from a body. Thus, as the Reynolds Number of an airfoil is increased, the boundary layer in the region of separation becomes turbulent with resultant delay in the separation of flow from the airfoil and, consequently, a

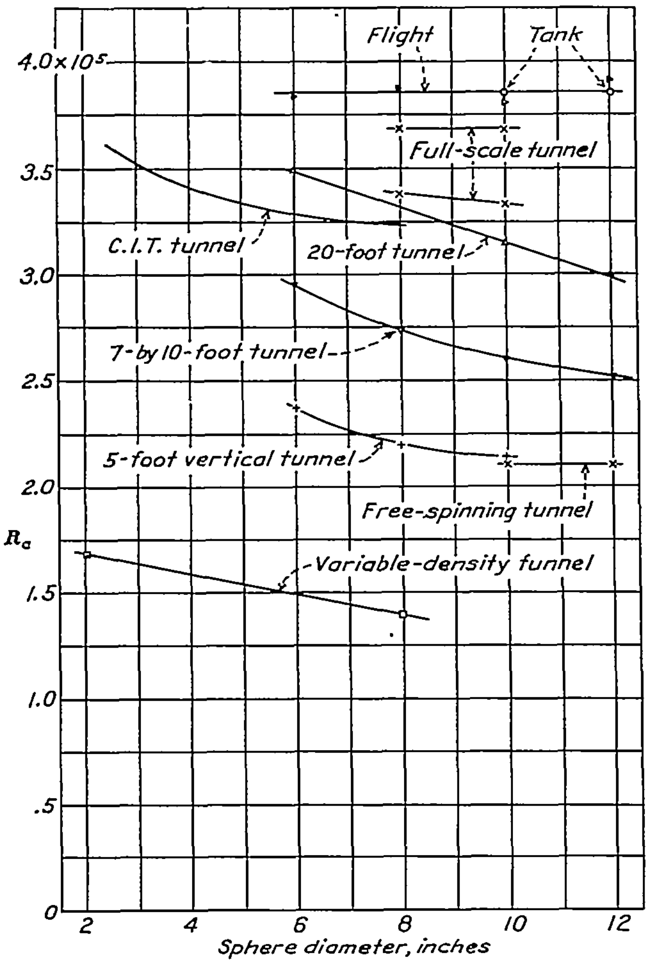


FIGURE 17.—Variation of critical Reynolds Number with sphere diameter for some of the wind tunnels listed in table I.

greater maximum lift coefficient. It has been found that the presence of initial turbulence in an air stream tends to cause this variation to take place at consistently lower values of Reynolds Number than would be the case in a nonturbulent stream and that, by multiplying values of test Reynolds Number in a turbulent stream by a factor depending in magnitude on the amount of turbulence present, it is possible to bring the variation of maximum lift of an airfoil with Reynolds Number as measured in a turbulent stream into reasonable agreement with the variation measured in a less turbulent stream (reference 18).

Comparison of the sphere tests in various wind tunnels indicates that the variation of the pressure coefficient with Reynolds Number in various turbulent streams may be brought into approximate agreement by a procedure similar to that adopted in the case of airfoils. Furthermore, the same value of the factor serves to correct sphere tests and airfoil tests from the same wind tunnel. If, then, the ratio of the value of the critical Reynolds Number for a sphere in free air to the value in a turbulent air stream be taken, the resulting constant is a factor by which the test Reynolds Number in the turbulent stream must be multiplied to obtain the Reynolds Number at which corresponding transition and separation phenomena occur in a nonturbulent stream. This ratio may be called the "turbulence factor" (T. F.) of the air stream in question.

In accordance with this definition, the turbulence factors for the N. A. C. A. wind tunnels have been

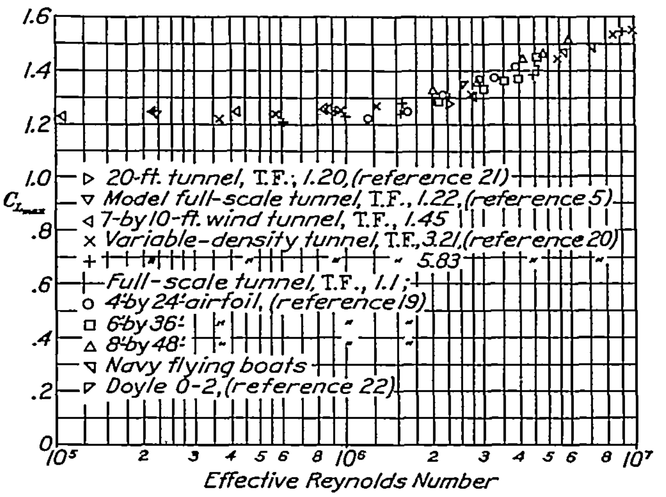


FIGURE 18.—Variation of $C_{L_{max}}$ with effective Reynolds Number for a Clark Y airfoil.

calculated, using in each case a mean value of the critical Reynolds Number found by testing the spheres of various size in each tunnel, and are given in table I. Values for the other tunnels listed in the table are given for comparison, although the fact that these values were computed without reference to sphere size or test position tends to render them not exactly comparable.

The value of the turbulence factor for a nonturbulent stream is, by definition, 1 and, since the critical Reynolds Number of the sphere in flight is the same as that in nonturbulent air, correction of wind-tunnel test Reynolds Numbers according to the foregoing turbulence factors is equivalent to correcting to the free-flight condition.

Figure 18 shows measured values of maximum lift coefficient of a Clark Y airfoil obtained from a variety of sources (references 5 and 19 to 22) and corrected to "effective Reynolds Number", i. e., test Reynolds Number times turbulence factor. It is interesting to note that when the results are corrected in this fashion they fall into a closely grouped band indicating a consistent variation of maximum lift of the Clark Y airfoil with Reynolds Number in free air. The data from the variable-density tunnel were obtained before the latest modifications were made to this tunnel and are therefore not representative of its present turbulence, as indicated by the different values of its turbulence factor in the figure and in table I. The dispersion of the experimental points obtained in the full-scale tunnel alone is almost as great as the dispersion of all the points plotted in this figure, which seems to indicate that apparent variations are a result of experimental inaccuracies throughout rather than of consistent differences caused by varying amounts of turbulence in the wind tunnels. Although flight determinations of maximum lift coefficient are subject to

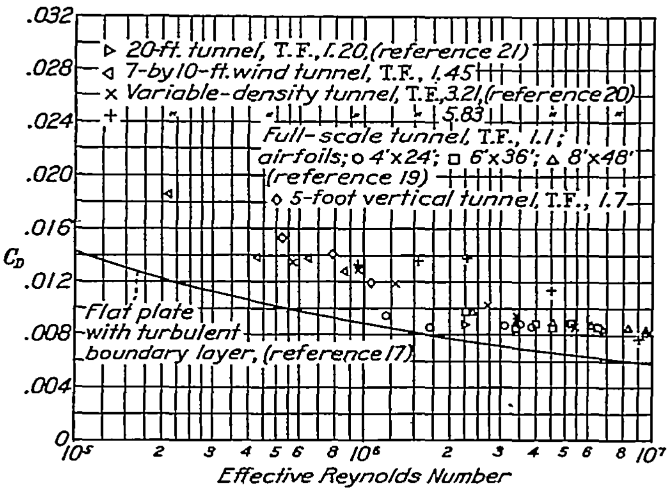


FIGURE 19.—Variation of C_D at zero lift with effective Reynolds Number for a Clark Y airfoil.

numerous sources of error, the results from tests in which special care has been taken to eliminate these errors appear to be in good agreement with the wind-tunnel results.

Figure 19 shows the variation of the drag coefficient at zero lift of the Clark Y airfoil with effective Reynolds Number, obtained from the same sources as the data of figure 18. An additional correction, however, is made to the drag data to make allowance for the difference in turbulent skin friction of the airfoil between the values of test Reynolds Number and effective Reynolds Number. This correction is made by deducting from the measured drag coefficient the change in skin friction involved in going from the test Reynolds Number to the effective Reynolds Number, as shown by the curve of turbulent skin friction of a flat plate against Reynolds Number in figure 19. An example of such correction with explanation is given in reference 18.

Although the dispersion of the drag data is greater than that for maximum lift, consideration of the possible errors involved in the tests indicates that the data show no disagreement. The most widely divergent points in figure 19 should probably be disregarded for the following reasons. In the full-scale-tunnel data, the points for the two lowest Reynolds Numbers are subject to large percentage errors owing to the small magnitude of the measured forces relative to the tare forces and balance capacity. In the variable-density-tunnel tests with increased turbulence (T. F. = 5.83), the model was mounted in such close proximity to the turbulence screen that the individual wakes were not fully dissipated. In this condition some doubt must exist regarding both air-stream calibration and effective turbulence.

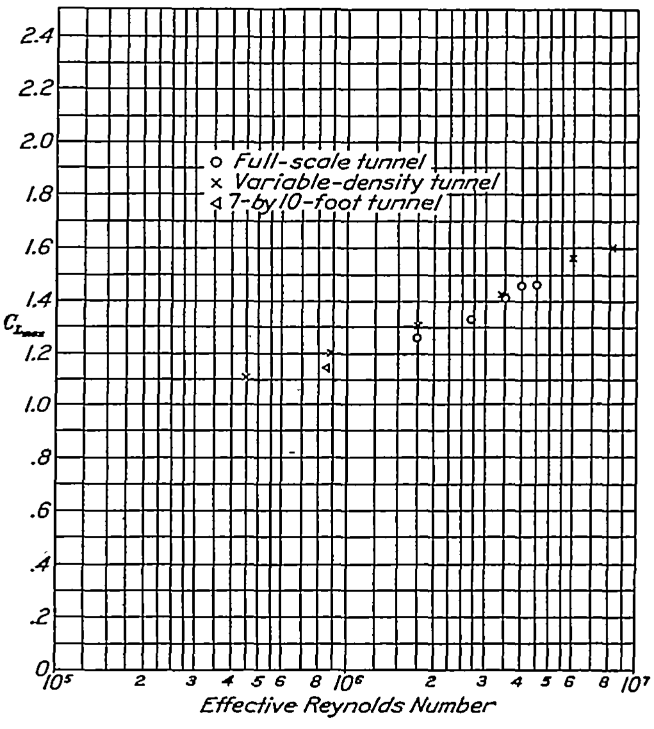


FIGURE 20.—Variation of $C_{L_{max}}$ with effective Reynolds Number for an N. A. C. A. 23012 airfoil.

Figures 20 and 21 show the variation of the maximum lift coefficient with Reynolds Number for the N. A. C. A. 23012 airfoil (reference 18) and the N. A. C. A. 2412 airfoil without and with a split flap. The data for the N. A. C. A. 2412 airfoil (fig. 21) are given in references 15 and 23, which present results of an extensive investigation of the effects of Reynolds Number and turbulence made at the California Institute of Technology. In figure 21(a) the results are plotted against test Reynolds Number for comparison with figure 21(b), in which they have been corrected to effective Reynolds Number. It is clear that when the results are corrected to effective Reynolds Number, a reasonably consistent variation of maximum lift of the N. A.

C. A. 2412 airfoil with Reynolds Number is established, although the results as plotted in figure 21(a) appear to show serious discrepancies between the maximum

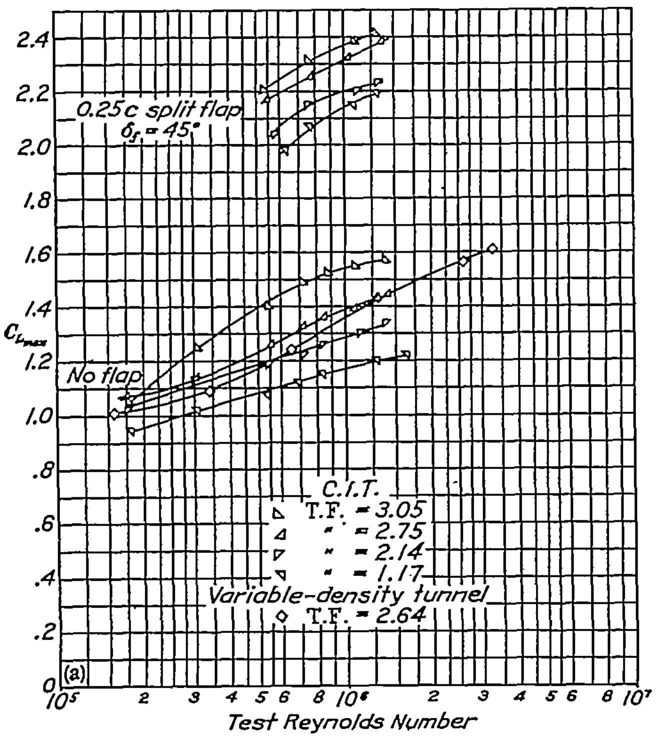


FIGURE (21 a)

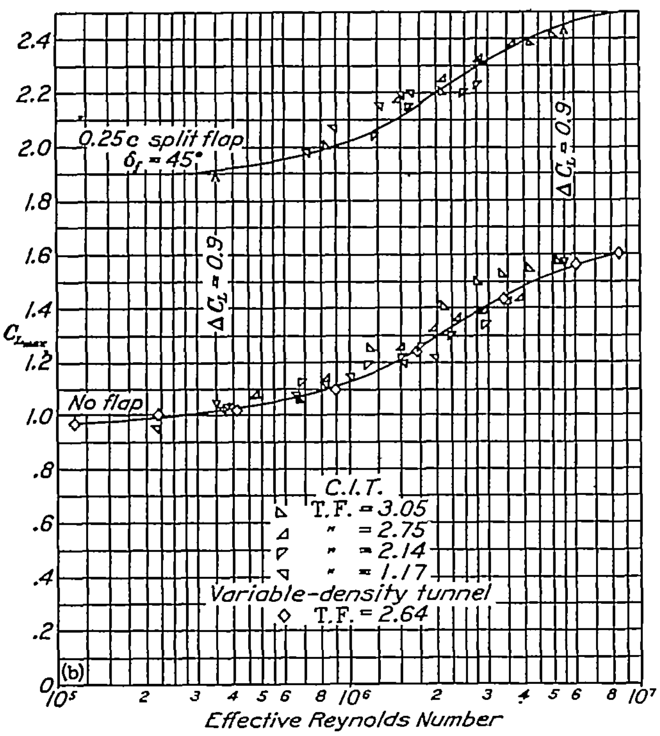


FIGURE 21 (a, b).—Variation of $C_{L_{max}}$ with test and effective Reynolds Number for an N. A. C. A. 2412 airfoil.

lift coefficients obtained with various degrees of turbulence. The scattering of the test points about the mean curve does not appear to be seriously greater than that found in the full-scale-tunnel tests with the Clark Y airfoil and is therefore believed to result from experimental inaccuracies rather than from consistent differences with the different amounts of turbulence employed. The apparently consistent differences may result from consistent errors caused by compressibility effect, model deflection under air load, difficulty of calibration of a highly turbulent air stream, and variation of critical Reynolds Number with sphere size.

In order to develop further the basis of the effective Reynolds Number concept, it is desirable to consider the conditions necessary for geometric similarity in aerodynamic tests. Four principal dimensions, relative to a linear dimension of the model, must be similar; namely, the thickness of the laminar boundary layer, the downstream distance of the point of transition from laminar to turbulent boundary layer, the thickness of the turbulent boundary layer, and the downstream distance of the point of separation. In streams having no turbulence the Reynolds Number serves as a criterion for similarity of all these factors but, when different amounts of turbulence are present in two different streams, dissimilarities of at least the last three items appear at the same test Reynolds Number, since the point of transition is moved forward by the presence of increased turbulence. If the test Reynolds Number of the model in the more turbulent stream is reduced to bring the point of transition into agreement, similarity is partly restored although the relative boundary-layer thicknesses are somewhat different. This procedure appears to be the most satisfactory method at present available for obtaining approximate similarity of tests in air streams with different amounts of turbulence and seems justifiable in cases where the direct effect of boundary-layer thickness is known, so that it can either be neglected or suitably corrected.

The use of sphere tests to indicate the relative values of Reynolds Number needed to give approximate similarity under different conditions of initial air-stream turbulence is based on the inference that when the sphere-drag coefficient C_D is equal to 0.3 $\left(\text{or } \frac{\Delta p}{q}=1.22\right)$ the point of transition has a given downstream location, relative to the sphere diameter, although the value of the Reynolds Number at which this occurs may vary widely, depending on the initial air-stream turbulence. The validity of this inference depends on the assumption that the different boundary-layer thicknesses have only secondary effects on the pressure distribution around the body, an assumption sufficiently common in wind-tunnel testing to need no special verification for the purposes of the present discussion. If it is further assumed that the effect of turbulence on boundary-layer transition is approximately the same for spheres and airfoils in spite of the different pressure gradients that may be involved, then the procedure required to obtain similarity in sphere tests should give approximate similarity for airfoil tests.

To summarize, it may be stated that the Reynolds Number serves as a criterion of geometric similarity of air flow about similar models in streams having zero turbulence; the effective Reynolds Number may possibly serve as a criterion of approximate geometric similarity in streams having different degrees of turbulence. Furthermore, a turbulence factor obtained from sphere tests may serve to indicate the approximate relation of effective Reynolds Number to test Reynolds Number for certain other aerodynamic bodies.

In the light of this discussion it is clear that for the data of figure 21 the test Reynolds Number has not served as a criterion of similarity. For all the maximum-lift data presented, however, the effective Reynolds Number does appear to have established the conditions of similarity, at least to a first approximation.

Perhaps there is less reason to regard the same effective Reynolds Number as a satisfactory criterion in the case of the drag coefficient, but it should at least be a more reliable criterion of similarity with respect to the point of transition than the test Reynolds Number. Here, however, the boundary-layer thickness exerts an appreciable influence, so after similarity with respect to transition has been obtained, a drag increment is required to allow for the dissimilar boundary-layer thicknesses. This procedure has been followed in several cases (references 18 and 24), partly because of the foregoing considerations and partly because it permits the presentation of all the data at the same value of the Reynolds Number. The data of figure 19 indicate that no disagreement results from this process as applied to the drag of the Clark Y airfoil at zero lift. Although certain doubts may be raised regarding the validity of the effective Reynolds Number concept as applied to the drag of airfoils, it is significant that the result obtained is in agreement with that predicted by a widely employed method of extrapolation (reference 25).

The limitations of the effective Reynolds Number concept are apparent from the foregoing discussion. Strictly speaking, its application is limited to effects resulting principally from the transition of the laminar boundary layer or from the interaction of this transition with flow separation. Where the effects associated with boundary-layer thickness are of primary importance the concept may still be applicable, but suitable correction for these effects must also be made and, if the effect is unknown but not negligible, the concept cannot be expected to give a clear interpretation of the phenomena involved.

A case of the failure of the concept may deserve mention. In certain unpublished tests of a slotted airfoil, a discontinuity observed in the curve of $C_{L_{max}}$ against Reynolds Number was attributed to the varying relation of boundary-layer thickness to slot size. Since both test Reynolds Number and point of transition affect this relation, it seems likely that neither test nor effective Reynolds Number will serve as a criterion of similarity in this case.

Consideration of these effects of turbulence, in combination with a method of correcting for them, suggests the possibility of extending the effective scale range of a wind tunnel for the measurement of certain aerodynamic coefficients by the introduction of artificial turbulence. The maximum effective Reynolds Number attainable is equal to the maximum test Reynolds Number times the turbulence factor. A certain arrangement of the variable-density tunnel having a turbulence factor of 5.8 gave the correct variation of $C_{L_{max}}$ with Reynolds Number for the Clark Y airfoil (see fig. 18), and it seems reasonable to expect that even higher values might be reached without affecting the interaction of scale and turbulence as applied to transition and separation phenomena.

CONCLUSIONS

1. The N. A. C. A. wind tunnels may be listed in order of increasing turbulence as follows:

   The full-scale tunnel.
   The 24-inch high-speed tunnel.
   The 20-foot tunnel.
   The model of the full-scale tunnel.
   The 7- by 10-foot tunnel.
   The 5-foot vertical tunnel.
   The free-spinning tunnel.
   The variable-density tunnel.

2. The effect of scale on the maximum lift coefficient of medium-camber, medium-thickness airfoils in a nonturbulent air stream may be obtained from tests in a turbulent stream by the application of a turbulence factor, obtained from sphere tests, to the test Reynolds Numbers of the models in the turbulent stream.

3. For determination of certain aerodynamic characteristics, the scale range of a wind tunnel may be extended to higher effective values of the Reynolds Number by the introduction of artificial turbulence into the air stream.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *February 4, 1936.*

APPENDIX

CORRELATION OF SPHERE DRAG AND PRESSURE TESTS

The air flow about a body that is not tapered to a point in the downstream direction is known to separate in the vicinity of the region where the pressure gradient on the surface of the body tends to oppose the normal direction of flow. (See also reference 14.) The low pressure on the surface of the body aft of the point of flow separation produces consequent large values of the drag coefficient. In the case of the sphere, this pressure drag is sufficiently large that, for purposes of approximate analysis, the skin-friction drag on the surface of the sphere may be neglected and the total drag of the sphere may be regarded as resulting from the pressure applied to the surface.

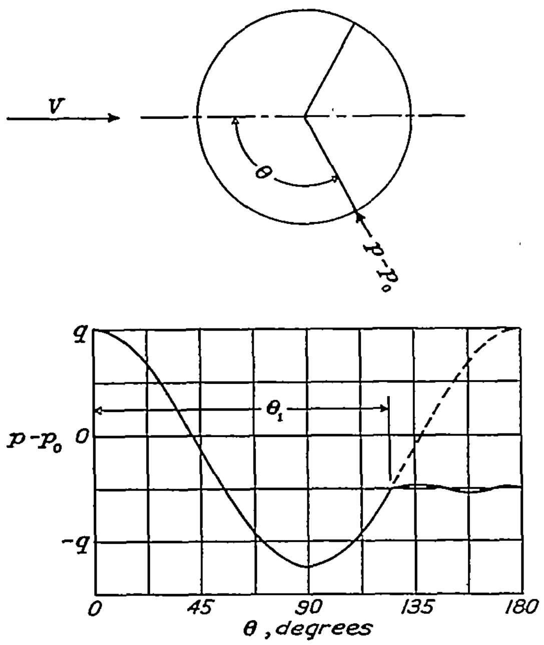


FIGURE 22.—Pressure distribution on a sphere.

Two phases of flow exist on a sphere in a stream of viscous fluid: that over the front portion, which approximates the theoretical flow in a nonviscous fluid; and an eddying wake region over the portion aft of the point of separation of the flow. If a sphere be considered cut by one branch of a circular cone with generating angle θ and with the apex at the center of the sphere (see fig. 22), then the pressure produced by the potential flow around the sphere at any circle of intersection of the sphere and cone is $\frac{p}{q}=1-2\frac{1}{4}\sin^2\theta$ (reference 26) and the drag coefficient of the upstream part of the sphere, by integration, is $C_D=\sin^2\theta\ (1-\frac{9}{8}\sin^2\theta)$ where p is the increment of pressure on the surface above the normal static pressure of the stream, and $q=\frac{1}{2}\rho V^2$. The theoretical pressure distribution expressed by the foregoing equation is shown in figure 22. If the point at which the flow separates from the surface of the sphere be designated θ_1, it has been found that the pressure aft of θ_1 on the surface of the sphere is approximately equal to the pressure at θ_1. In other words, the surface of the sphere in the wake region is subjected to a uniform pressure approximately equal to the theoretical pressure at the point of separation of flow. It is possible then to express the pressure drag on the rear portion as

$$D=-\int p\,dA=-p\pi r^2\sin^2\theta_1$$

or

$$C_D=-\frac{p}{q}\sin^2\theta_1$$

It is now possible to express the total drag coefficient of the sphere as equal to the sum of the drag due to the theoretical distribution ahead of the point of separation and the drag in the wake region behind the point of separation,

$$C_D=\sin^2\theta_1\left(1-\frac{9}{8}\sin^2\theta_1\right)-\frac{p}{q}\sin^2\theta_1$$

Collecting and substituting for p/q,

$$C_D=\frac{9}{8}\sin^4\theta_1$$

It is also possible to calculate the pressure difference between the front and the rear portions of the sphere as a function of θ_1. At the front $\frac{p}{q}=1$, or front pressure equals q. Aft of the point of separation,

$$\frac{p_1}{q}=1-2\frac{1}{4}\sin^2\theta_1$$

and the difference between the front and rear pressures,

$$\Delta p=q-p_1=q-\left(q-2\frac{1}{4}\sin^2\theta_1\ q\right)=2\frac{1}{4}\sin^2\theta_1\ q$$

or

$$\frac{\Delta p}{q}=2\frac{1}{4}\sin^2\theta_1$$

Substituting in the equation for C_D,

$$C_D=\frac{9}{8}\left(\frac{4}{9}\frac{\Delta p}{q}\right)^2=\frac{2}{9}\left(\frac{\Delta p}{q}\right)^2$$

Results from tests in the 7- by 10-foot tunnel and in the full-scale tunnel, in which corresponding drag and pressure tests were made, are plotted in figure 23 together with a curve plotted from the foregoing equation showing the relation between the drag and pressure coefficients. The tests cover a wide range of values of air-stream turbulence, the 7- by 10-foot wind tunnel being very turbulent with the grid in place and comparatively free from turbulence without the grid. The air stream in the full-scale tunnel is very nearly equivalent to nonturbulent air. The plotted results indicate no consistent difference in the relation between C_D and $\Delta p/q$ with the various amounts of turbulence. This

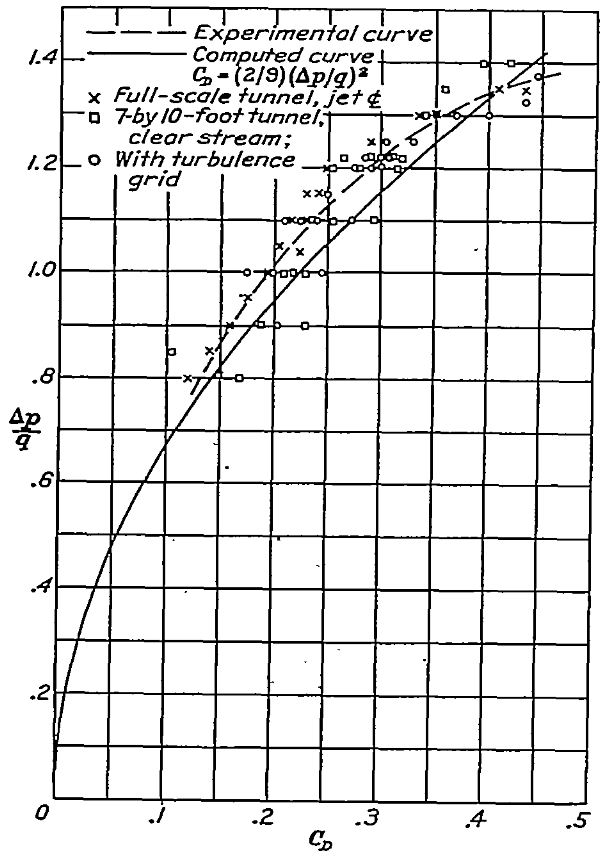


FIGURE 23.—Correlation of sphere drag and pressure measurements.

agreement is taken as evidence that the correlation between drag and pressure coefficients as found here is independent of the degree of air-stream turbulence and that a reliable indication of the critical Reynolds Number may be obtained from sphere pressure tests under any conditions in which it could be obtained from sphere drag tests. The mean value of $\Delta p/q$ at $C_D=0.3$ is 1.22. Thus, in the sphere pressure tests the Reynolds Number corresponding to the value $\frac{\Delta p}{q}=1.22$ is taken as the critical Reynolds Number. It is considered worthy of mention that the German tests correlating drag and pressure coefficients (reference 14) made at only one degree of air-stream turbulence corroborate the relation between drag and pressure found in the present tests.

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TABLE I

VALUES OF CRITICAL REYNOLDS NUMBER AND TURBULENCE FACTOR FOR VARIOUS WIND TUNNELS AND IN FREE AIR

Air stream	Remarks	Critical Reynolds Number R_c	Turbulence factor (T. F.)
Free air	N. A. C. A. flight	385,000	1.0
Still air	N. A. C. A. tank	385,000	1.0
N. A. C. A.:			
Full-scale tunnel	Average value	350,000	1.1
24-inch high-speed tunnel	4-inch sphere	350,000	1.1
20-foot tunnel	Average value	320,000	1.2
Model full-scale tunnel	8-inch sphere	315,000	1.2
7- by 10-foot tunnel	Average value	270,000	1.4
5-foot vertical tunnel	do	225,000	1.7
Free-spinning tunnel	Normal test level	211,000	1.8
Variable-density tunnel [1]	Average value	150,000	2.6
R. A. E.:			
5-foot tunnel	do	250,000	1.5
7-foot tunnel	2 tunnels	185,000	2.1
N. P. L. compressed-air tunnel		190,000	2.0
Göttingen:			
Large tunnel		320,000	1.2
Small tunnel		280,000	1.4
Propeller tunnel		310,000	1.2
D. V. L. 1.2-meter tunnel	Average value	325,000	1.2
Braunschweig tunnel	do	300,000	1.3
Turin tunnel		200,000	1.9
Japanese navy 2.52-meter tunnel		310,000	1.2
Mitsubishi Co. tunnel		330,000	1.2
Kawanishi Co. tunnel		270,000	1.4
Aichi Tokei Co. tunnel		270,000	1.4
C. I. T. 10-foot tunnel	Average value	335,000	1.1
Akron vertical tunnel	do	250,000	1.5
Bureau of Standards:			
10-foot tunnel		230,000	1.7
4.5-foot tunnel		265,000	1.5
3.0-foot tunnel		270,000	1.4
M. I. T. 7.5-foot tunnel		186,000	2.1
Wright Field 5-foot tunnel	Average value	260,000	1.5
Free air	D. V. L. test (corrected to $\frac{\Delta p}{q}=1.22$)	385,000	
Do	C. I. T. test	364,000	
Do	M. I. T. test	290,000	

[1] Reference 11.